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VISIBILITY CONDITIONS OF NOCTILUCENT CLOUDS

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ABSTRACT. The trajectories of light rays in polar coordinates as well as the corresponding indices of refraction and refraction angles are calculated with the help of electronic machines according to the author's formulas. The results are given in the tables presenting light trajectories within the whole interval of altitudes of the closest approach, namely from 10 to 60 km every 2 km. One can consider that the atmospheric layers within the altitude of 10 km, that is in the region of the troposphere, are in fact opaque to the passing horizontal rays; on the other hand the rays passing at the altitude of more than 40-50 km do not experience a noticeable refraction or absorption.

The necessary auxiliary tables for the determination of the optical systems of the atmosphere in relation to the refraction of the horizontal rays which pass through it, were calculated according to our formulas with the aid of electronic computers at the USSR Astronomical Council of the Academy of Science. These tables show the light ray trajectories found in the polar coordinates r, φ (the radius-vector is calculated from the center of the Earth and the amplitude angle is calculated from the point of closest proximity to the Earth's surface), as well as the corresponding indexes and angles of refraction. The light trajectories are given within the whole interval of altitudes of the closest proximity, particularly from 10 km. to 60 km. and at 2 km. intervals of the parameter h_o. The atmospheric layers within an altitude of 10 km., i.e. in the region of the troposphere, can be considered, in effect, as opaque to the passing of horizontal rays; on the other hand, the rays passing at an altitude of more than 40-50 km. do not experience a noticeable refraction or absorption. /26*

As we know, attenuation of the light which falls onto noctilucent clouds depends on the usual extinction and partially complete absorption (for example, in the ozone layer) which they experience. It also depends on the refraction dispersion that is caused by the divergence of a pencil of beams which passes through the atmosphere at different altitudes h_o (see Fig. 1).

*) Numbers in margin indicate pagination of foreign text.

The refraction dispersion factor f, which characterizes the apparent attenuation of illumination, is represented by the expression

$$f = \frac{d(n_0 r_0) r\, dh_0}{dh_0 n_0 r_0\, dh},$$

where $r_0 = R + h_0$ (R is the radius of the Earth); r is the radius-vector of the examined point of the trajectory, while $r = R + h$ and n_0 is the index of refraction for the minimal distance h_0 of a given trajectory from the Earth's surface.

It can be accepted as a given, that the light rays undergo refraction and are distinguished by a certain curvature up to the amplitude angle $\varphi_1 = 5°$ (for the indicated limits of h_0), to which the vector r_1 corresponds, and that their further extension is in straight lines. In this case, the radius-vector r for the assigned angle ζ between r and the direction to the sun will be

$$r = R + h = \frac{r_1 \sin \zeta_1}{\sin(\zeta - 2\mathrm{Refr}_1)},$$

where $\zeta_1 = 90 - \varphi_1 + \mathrm{Refr}_1$, and Refr_1 is the total horizontal refraction for a given trajectory.

The values of h and f, calculated according to these formulas, are given in Table 1 for three different angles of ζ. They are chosen in such a way that the range of the altitudes obtained would include the altitude at which the clouds are encountered.

The results, which are given in Table 1, are shown graphically in Fig. 2.

Using Table 1, we can pose the problem of determining the illumination conditions of a noctilucent cloud layer which is situated at the altitude h_0 for rays passing at different minimal altitudes h_0 (Fig. 3). Let us assign the zenith distance of the Sun $\zeta_\odot$ for the position of the observer M situated on the earth's surface and the parameter h_0, which represents a given light trajectory. In this case the zenith distance r of the illuminated sector K of the noctilucent cloud's surface situated at a given altitude h is given by the expression

$$\operatorname{tg} z = \frac{\sin \alpha}{\cos \alpha - \frac{R}{R+h}},$$

where $\alpha = \zeta_{\odot} + \zeta_2 - 2\ \mathrm{Refr}_1 - 180°$ is an angle originating at the center of the Earth and contained between the directions M and K. The angle ζ_2 contained between the radius-vector r and a tangent to the light trajectory is obtained from the expression

$$\sin\zeta_2 = \sin\zeta_1 \frac{r_1}{R+h},$$

in which r_1 and ζ_1 are related to the angle of amplitude $\varphi_1 = 5°$ and are derived from the function of the parameter h_0 from our main auxiliary tables. The results of such calculations are given in Table 2.

TABLE 1 /27

h_0, км	Refr	$\zeta = 98°$		$\zeta = 99°$		$\zeta = 100°$	
		h, км	f	h, км	f	h, км	f
10	10'34",12	67,89	—	83,995	—	102,16	—
12	7 44, 13	71,185	0,595	87,491	0,5653	105,86	0,538
14	5 34, 16	74,19	0,664	90,647	0,6363	109,17	0,611
16	3 59, 45	76,93	0,721	93,499	0,6960	112,134	0,672
18	2 51, 33	79,55	0,794	96,218	0,7741	114,95	0,754
20	2 03, 04	81,85	0,862	98,568	0,8476	117,35	0,833
22	1 29, 02	84,13	0,8855	100,892	0,8730	119,72	0,861
24	1 04, 63	86,34	0,9157	103,131	0,90645	121,99	0,889
26	0 47, 28	88,49	0,9374	105,309	0,9260	124,20	0,915
28	0 34, 63	90,61	0,9541	107,445	0,9494	126,35	0,937
30	0 25, 43	92,70	0,9665	109,551	0,9634	128,48	0,958
32	0 18, 83	94,77	0,9753	111,634	0,9730	130,57	0,968
34	0 13, 89	96,83	0,9822	113,702	0,9791	132,65	0,9775
36	0 10, 31	98,75	0,9865	115,760	0,9850	134,72	0,983
38	0 7, 69	100,92	0,9898	117,808	0,9895	136,78	0,9875
40	0 5, 78	102,90	0,9928	119,849	0,9925	138,82	0,991
42	0 4, 32	104,98	0,9949	121,890	0,9941	140,872	0,9938
44	0 3, 30	107,00	0,9963	123,922	0,9960	142,914	0,9965
46	0 2, 54	109,03	0,9978	125,953	0,9970	144,95	0,9978
48	0 1, 93	111,05	0,9985	127,983	0,9980	146,99	0,9990
50	0 1, 53	113,08	0,9994	130,013	0,9994	149,02	0,9995

TABLE 2 /28

	100°	102.5°	105°	107.5°	110°
h_o = 10 km h_o = 40 km	39°35' 75 45	77°15' 84 10	84°45' 88 17	88°35' 90 46	91°1.5' 92.53

The values of z are indicated in Fig. 4. Shown along the abscissa axis are the zenith distances of the Sun from the observer's position.

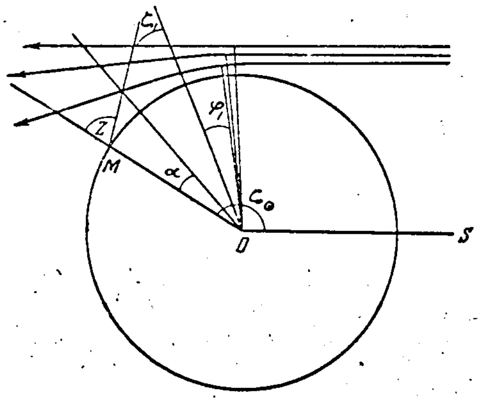

Fig. 1. Course of rays in atmosphere

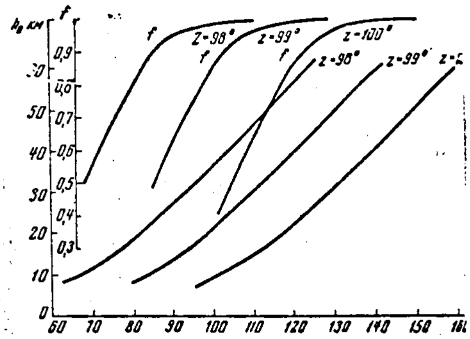

Fig. 2. Calculated values of h and f

The upper curve represents the visibility boundary of the noctilucent clouds whose boundary corresponds to the minimal altitude of a light ray when h_o = 10 km., and the lower curve represents the boundary of visibility when h_o = 40 km. Occurring between these curves is the entire range of illuminance of the noctilucent clouds which is related to the presence of refraction dispersion, and extinction caused by atmospheric aerosol, and complete absorption by ozone in the Shapyui belt.

As can be seen, the noctilucent clouds could have been observed at a considerable altitude above the horizon during the period of bright twilight. However, it should be noted that they cannot be distinguished against the bright background of the sky. After the twilight ends (when $\zeta_{\odot} \geqslant 106°$) the upper boundary of illumination quickly hugs the horizon and therefore the Sun is in such positions that the noctilucent clouds, for all practical purposes, cannot be seen. Therefore, the most favorable conditions for their observation from the earth's surface exist during a weak twilight.

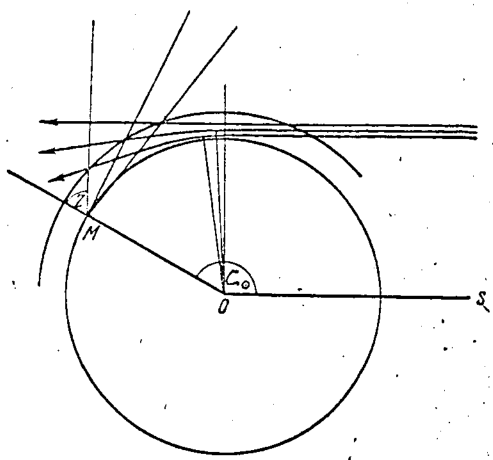

Fig. 3. Conditions of illumination of a noctilucent cloud layer.

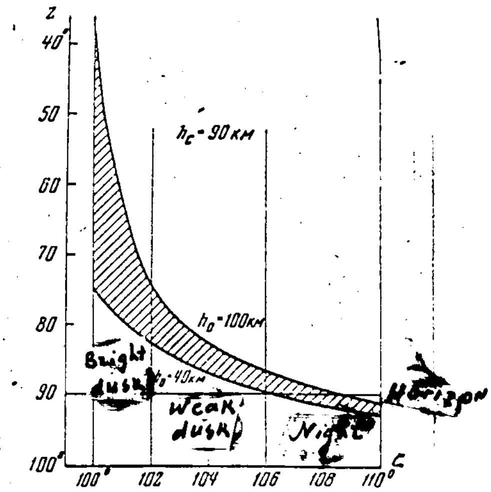

Fig. 4. Calculated zenith distances of the illuminated sectors of the noctilucent clouds.

It is quite apparent that it would be very desirable to /29 observe the noctilucent clouds from high mountain positions, where the horizon line would be considerably lowered and where the local pollution of the lower air layers is absent. The filamental structure of the noctilucent clouds facilitates the calculation of the twilight sky background. Usually the noctilucent clouds are observed under conditions of illumination which are characteristic of the transitional region between h_0 = 10 km. and 40 km. This region is characterized by its weak transparency for yellow-green, but not for blue and extreme red rays, due to the presence of ozone. Perhaps this can explain the peculiarities of the noctilucent cloud type. It would be interesting to observe the drop in the brightness of these clouds, for this drop would explain the transitional zone for different wavelengths.

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